CLNS 80/466

CESR: THE FIRST YEAR*

M. Billing, E. Blum, J. Kirchgessner, R. Littauer, B. McDaniel, R. Meller, D. Morse, S. Peck, S. Peggs, D. Rice, G. Rouse, J. Seeman, K. Shinsky, R. Siemann, R. Sundelin, R. Talman, M. Tigner and E. von Borstel.

* Work supported by the National Science Foundation

Presented at the XI International Conference on High Energy Accelerators in CERN, July 1980.

CESR: THE FIRST YEAR[a)]

The CESR Operations Group[b)]

ABSTRACT

The first year of operation of CESR, the Cornell Electron Storage Ring, is described. The machine parameters are reviewed, and a summary given of the effectiveness of CESR as an instrument for high energy physics research. The filling process is outlined in some detail, with emphasis given to those aspects unique to CESR. The results of a number of machine studies programs are summarized. Finally, prospects for the near future are described.

1. THE CESR MACHINE PARAMETERS

CESR[1)] is an electron-positron storage ring in which one bunch of each type of particle is stored, providing collisions at two interaction regions.[2,3)] In addition, synchrotron radiation from the electron beam is used by the CHESS (Cornell High Energy Synchrotron Source) laboratory. The maximum design energy is 8 GeV per beam, although the present operating point is at or below 5.5 GeV. The average luminosity during physics runs is 10^{30} cm^{-2}sec^{-1}. Maximum luminosity of 3×10^{30} cm^{-2}sec^{-1} has been reached with 8 mA beams. Accumulated luminosity of 50 nb^{-1} per day is obtained on the average, with peaks exceeding 70 nb^{-1} per day.

The CESR lattice is of the FODO type, with each half cell consisting of a dipole, quadrupole, and sextupole magnet. Vertical correction windings are fitted to the sextupoles, and horizontal correctors to the dipoles. The normal dipoles have a bending radius R=87.9 m, but "hard bends" near each interaction region have R = 31.6 m and 34.8 m. The circumference is 768 m.

Vacuum of 10^{-9} to 10^{-8} Torr is maintained by distributed ion pumps in chambers coupled to the extruded aluminum beam pipe, and which use the magnetic field of the dipole magnets.[4)] The RF system consists at present of a single accelerating module of 14 cavities operating at 500 MHz and 180 kW power.[5)] Beams of electrons and positrons are injected through transfer lines from the Cornell electron synchrotron, a process that will be described in more detail below. Figure 1 shows schematically CESR and its users, emphasizing the more irregular parts of the lattice. Figure 2 shows the calculated enveloped functions for our current luminosity lattice.

2. MACHINE PERFORMANCE FOR HIGH ENERGY PHYSICS

The CESR ring was closed on April 1, 1979, and an electron beam was stored on April 13. Positrons were first stored on May 28, and the first measureable luminosity recorded on August 18. A short physics run was carried out in October, and was followed by 3 runs of approximately 6 weeks duration beginning in November 1979, February and April 1980. The energy for these runs ranged from 4.7 to 5.3 GeV per beam.

The machine performance for the 3 major physics runs is summarized in Figure 3. Figure 3a shows the fraction of time assigned to high energy physics expended in repairs and maintenance, filling and tuning, and running. Figure 3b shows the luminosity, averaged

a) Work supported by the National Science Foundation.

b) M. Billing, E. Blum, J. Kirchgessner, R. Littauer, B. McDaniel, R. Meller, D. Morse, S. Peck, S. Peggs, D. Rice, G. Rouse, J. Seeman, K. Shinsky, R. Siemann, R. Sundelin, R. Talman, M. Tigner and E. von Borstel.

over total time assigned to physics running, and averaged over time with stored beams.

The goals of the machine studies programs are to reduce the time required for filling and tuning, and to increase the average luminosity with stored beams. Figure 3 indicates we have been more successful in the latter endeavor.

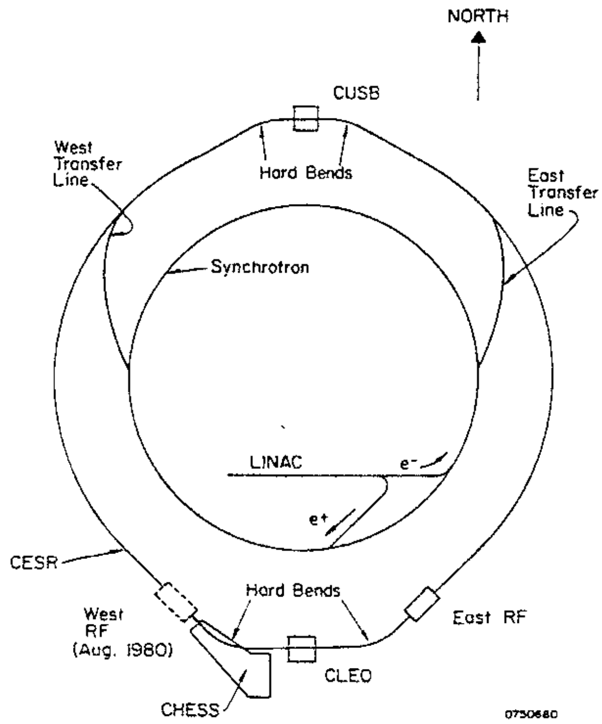


Fig. 1: CESR and its users. General features of the accelerator complex are shown schematically. CLEO: Cornell/Harvard/Rochester/Rutgers/Syracuse Vanderbilt collaboration. CUSB: Columbia/Stony Brook/Louisiana State/Max-Planck Inst. collaboration. CHESS: Cornell High Energy Synchrotron Source.

3. THE CESR FILLING SEQUENCE

CESR is loaded with electrons and positrons accelerated to 5.5 GeV in the Cornell Electron Synchrotron. At this energy, the injection rate is limited by damping time to 30 Hz. The linac/synchrotron combination is unable to supply a sufficient quantity of positrons in single bunches at 30 Hz to fill CESR in an acceptable time, so a more complicated positron injection scheme has been devised.[6] This scheme consists of two parts: the injection of multiple bunches of positrons into CESR, and the coalescing of the bunches into a single bunch.

The injection part of the cycle is shown in Figure 4. Approximately 50 bunches of positrons, at 42 ns. intervals, are accelerated in the synchrotron and transferred to CESR via the West transfer line at the 30 Hz injection rate. Each newly-accelerated group of bunches is transferred to the same CESR buckets as each previous group, so the build-up of charge in the CESR buckets, as seen by a button detector, is a reflection of the synchrotron fill pattern. This pattern has a gap of approximately 500 ns. due primarily to the turn-off time of the pulsed inflector magnet at the junction between the linac and the synchrotron.

After approximately 2 minutes of multiple-bunch positron injection into CESR, the bunches are coalesced into a single bunch at the location of the gap in the original fill pattern. This process is shown in Figure 5, and works only because the difference in circumference between CESR and the synchrotron is exactly one bunch spacing.

Each bunch is extracted from CESR and re-injected into the synchrotron via the East transfer line. It then circulates in the synchrotron a sufficient number of turns to allow it to overtake the other stored bunches in CESR, and is then re-injected via the West transfer line into the gap in the CESR fill pattern. The next bunch extracted from CESR circulates one less turn in the synchrotron, and then is re-injected into CESR in coincidence with the first bunch. In this way each stored bunch in CESR is removed from its original bucket and re-injected into the bucket all the positrons will occupy when there are colliding beams.

The process of filling and coalescing is repeated 6 to 10 times, requiring about 20 minutes, to store 8 mA of positrons. The efficiency of the coalescing process is typically 15% - 20%, although 30% has been achieved.

The process of electron filling is more straightforward, since the synchrotron can provide sufficiently intense single bunches of electrons to fill CESR directly. Single bunches of electrons are accelerated in the synchrotron and injected into the proper CESR bucket via the East transfer line. Typically less than 5 min. is required to fill to 8 mA.

To date, positron filling has been carried out at 5.5 GeV. Since January 1980 when electrostatic separator plates were installed, electron injection is also at 5.5 GeV. The

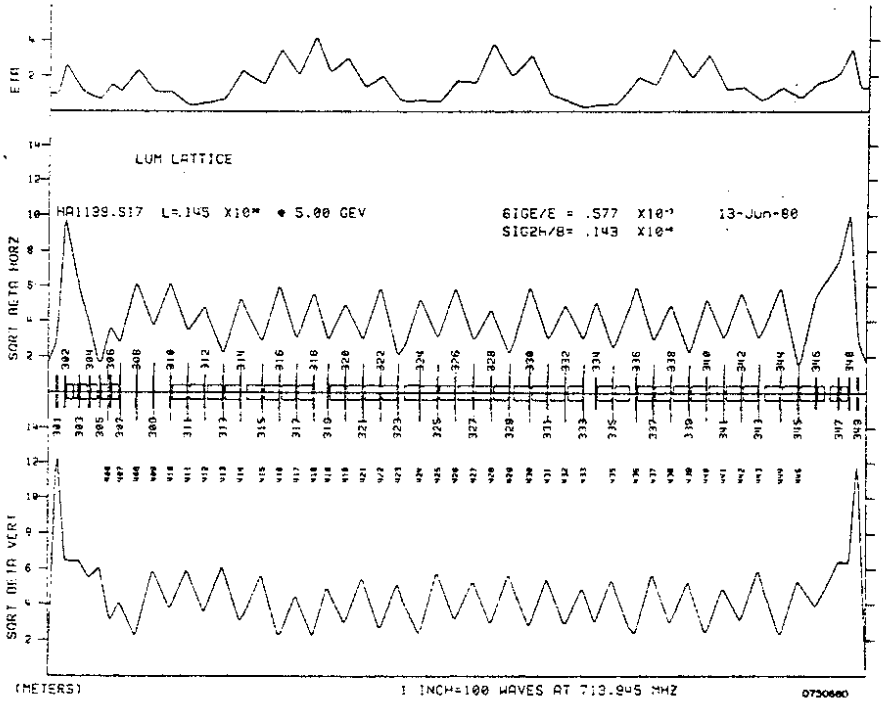


Fig. 2: Envelope functions for one-half of CESR, current luminosity lattice.

two stored beams are carried to the operating energy before the separators are turned off. Table 1 lists the major steps of the filling sequence, and the approximate time required for each step. For physics runs, equal beams of 8 to 9 mA are used, but single positron beams of 18 mA and electron beams of greater than 40 mA have been injected.

4. BEAM DIAGNOSTICS

The primary electrical diagnostic for beam intensity and position is the button detector system. Approximately 100 sets of 4 discs ("buttons") are installed in the beam chamber in such a way that sums and differences of various combinations of the button signals yield the radial and vertical position of the center of the bunch. The raw button signals are processed locally before being sent to the control room as "stretched" pulses.

An example of an orbit measured with this system is shown in Figure 6a. Figures 6b and 6c show the results of horizontal displacement and angle bumps, respectively, centered at the North interaction region.

The orbit measuring apparatus may be used in conjunction with a "pinger" magnet to make a rapid global measurement of the square root of the horizontal envelope (beta) function. The pinger is used to kick the single stored bunch horizontally on one turn only, and the orbit is measured on successive turns after the kick. With the pinger running repetitively at 30 Hz, about 20 seconds is required to measure the orbit of a particular turn after the kick. The superposition of many of these orbits yields a picture like that of Figure 7. Such a picture is useful for detecting assymetries in the

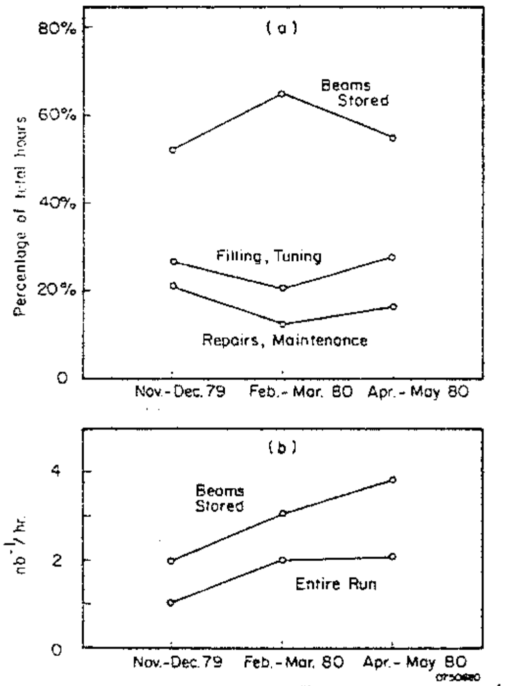


Fig. 3: CESR performance during first 3 major physics runs. a) Relative time spent running, filling, tuning, and for repairs and maintenance. b) Luminosity (nb^{-1}/hr.) with beams stored, and averaged over entire run.

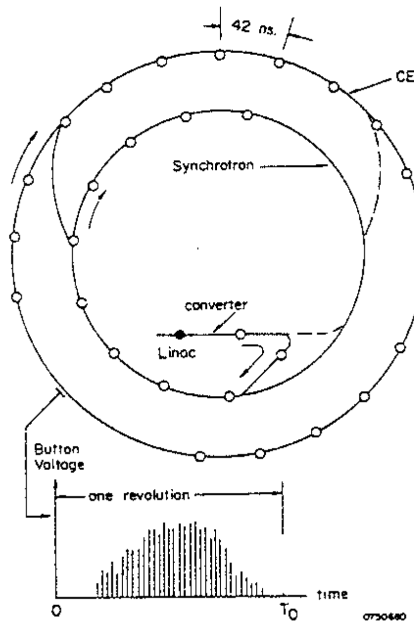


Fig. 4: Multi-bunch positron filling. Dashed lines indicate inactive portions of accelerators.

envelope function, but the absolute magnitude of beta is more accurately measured by changing the strength of a quadrupole by a known amount and measuring the corresponding change in betatron tune.[7)]

The off-energy (eta) function may also be measured using the beam detectors. In this base, the RF frequency is changed by a small amount, typically ±10 kHz, and the orbit displacement measured. The eta function is related to the frequency shift and the orbit displacement through the momentum compaction factor.

One button set is connected directly to the control room via broadband coaxial cable. The signals from these cables are used to drive a sampling oscilloscope, providing a measurement of bunch length and beam current. In addition, pairs of these signals are used to drive a differential amplifier whose output is connected to a spectrum analyzer. The betatron tunes of the machine are measured by observing the natural frequencies excited by a magnetic "shaker" whose frequency is controlled by the spectrum analyzer tracking oscillator. The synchrotron tune is measured by observing the sidebands of the rotation frequency, 390 kHz.

To complement the electrical button detectors, two optical systems monitor visible synchrotron light from the electron and positron beams. The intensity of the light from

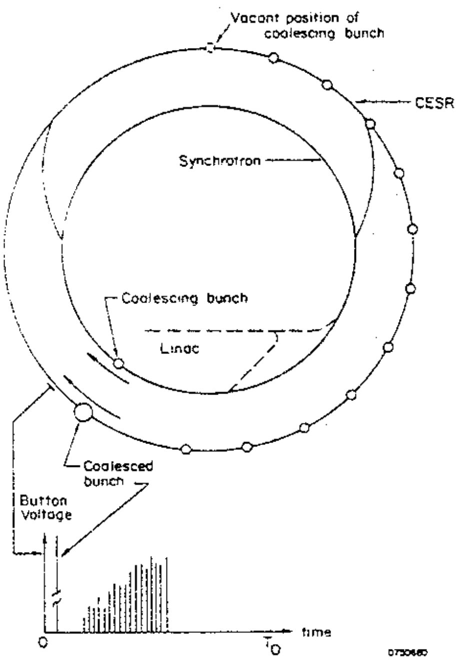


Fig. 5: Positron coalescing. Coalescing bunch is about to be extracted from the synchrotron and injected into the previously-coalesced bunch in CESR.

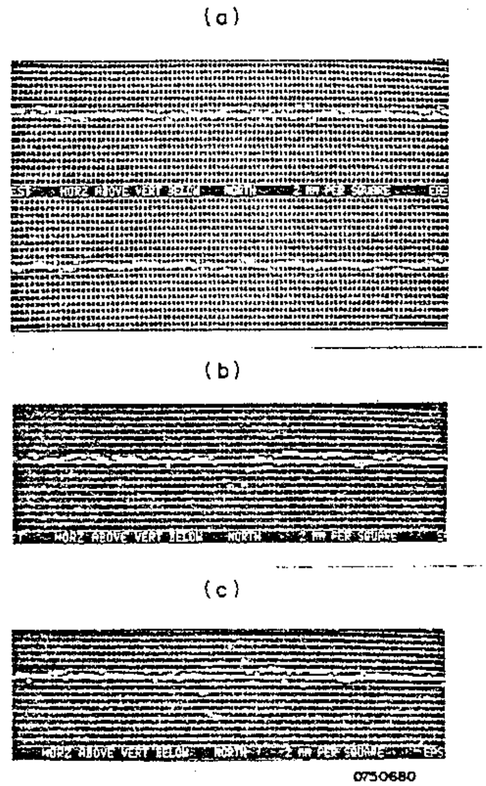


Fig. 6: Measured orbits from button detectors. a) Unperturbed orbit. b) Horizontal orbit with displacement bump at North crossing point. c) Horizontal orbit with angle bump at North crossing point.

Table 1

CESR Filling Sequence

1.	Cycle magnets and restore positron injection conditions in CESR. Start up linac and synchrotron and recover positron beam.	5 min.
2.	Minor tuning to optimize positron filling and coalescing	5 min.
3.	Fill and coalesce positrons	20 min.
4.	Restore electron injection conditions in CESR. Recover electron beam in synchrotron.	10 min.
5.	Fill with electrons	5 min.
6.	Ramp to luminosity optics and final energy	5 min.
7.	Collide beams, fine tuning for lifetime and to minimize trigger rates.	10 min.
		60 min.

each beam is used to provide a display such as that shown in Figure 8, in which the rates of decay and lifetimes of the beams are continuously monitored.

An image of the cross-section of the beam is focussed on a ground glass screen and viewed with a television camera. This image is also scanned vertically and horizontally across slits so the intensity of the light transmitted through each slit as a function of time is proportional to the corresponding vertical or horizontal profile of the beam. These diagnostics are shown in Figure 9. With the known properties of the optical system, and the beta functions at the observation points, the horizontal and vertical beam emittances can be measured.

Another important beam diagnostic is the luminosity measuring systems installed at each interaction region. Since the luminosity depends on the beam cross-section at the crossing points, we have another check on the beam emittances. Table 2 summarizes the results of those diagnostics applied to measurements of the beam bunch dimensions in the luminosity optics. The rms energy half-width, and the longitudinal and transverse half-widths at the crossing points are given and the corresponding diagnostics indicated.

Table 2

CESR Beam Bunch Characteristics, 4.7 - 5.3 GeV

Parameter	Value	Diagnostic	Comment
σ_E	3 MeV	Width of Upsilon Peak	Agrees with single particle theory.
σ_Z	2.5 cm	a) Vertex distribution b) Button signal time structure.	Agrees with single particle theory.
σ_x^*	0.9 mm	Horizontal emittance and energy width from theory, measured β_x^*	Luminosity optics $\beta_y^* = 11$ cm, currents less than 4 mA.
σ_y^*	0.02 mm	a) Vertical emittance from optical measurement, measured β_y^* b) Measured luminosity, beam currents, σ_x^*	Luminosity optics, $\beta_y^* = 11$ cm, currents less than 4 mA.

5. TUNING PROGRAMS

The CESR control system[8,9] is designed to allow individual control of each magnetic element, except the dipole bending magnets which are all connected in series. This great flexibility is sometimes useful, but in normal operation programs are used which allow the machine control computer to address groups of elements to perform specific tasks. A few of the more frequently-used programs are described in this section.

5.1 Magnet Cycling

Before each fill, all magnets are ramped through a degaussing cycle to remove the magnetic "memory" of the previous fill.

5.2 Orbit Corrections

Independent horizontal and vertical orbit smoothing is carried out by programs which read the beam position around the ring from the button detectors, and make appropriate adjustments to the horizontal or vertical correction winding currents.

5.3 Energy Ramping

Two techniques are generally used to change the machine energy from the injection energy to the final energy. For large energy changes (>50 MeV), all magnets are linearly ramped together between previously-established sets of conditions. Small energy changes to reach the final energy are then carried out using a program which allows the operator to choose a pre-determined energy increment, and ramps all magnets proprotionately.

5.4 Fine Tuning

A number of programs have been found useful for improving luminosity and reducing the detector trigger rates. These include:

i) Independent fine control of the horizontal and vertical betatron tunes.

ii) Independent control of the horizontal and vertical sextupoles, thereby changing the corresponding chromaticities.

iii) Static displacement and angle bumps, as shown in Figure 6 b) and c). Although these are usually applied at the interaction regions and injection points, they may be used at any point around the ring.

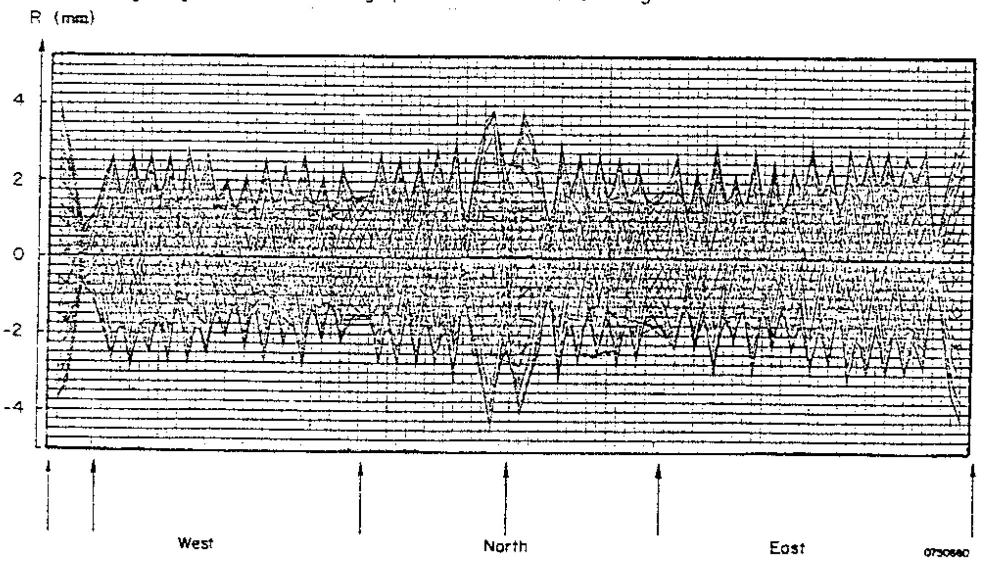
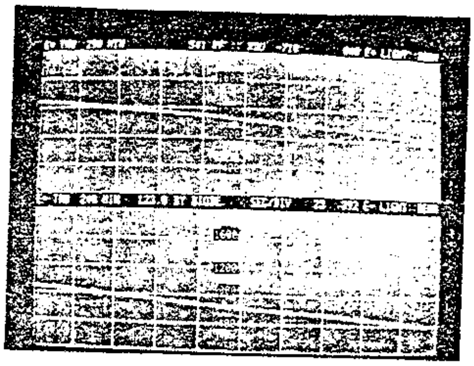


Fig. 7: Horizontal envelope function from "pinged" orbits. Arrows indicate positions of missing detectors.



0750680

Fig. 8: Beam lifetime measurements from synchrotron intensity.

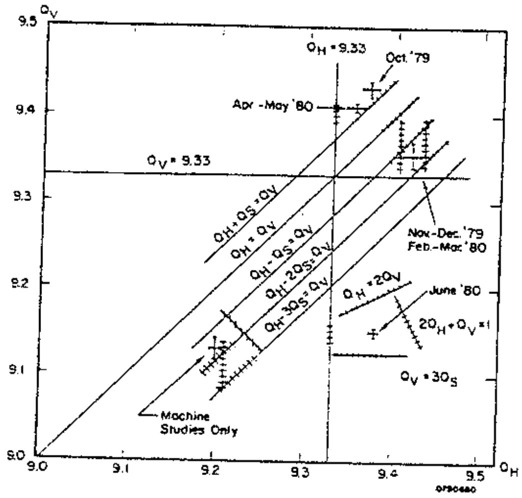
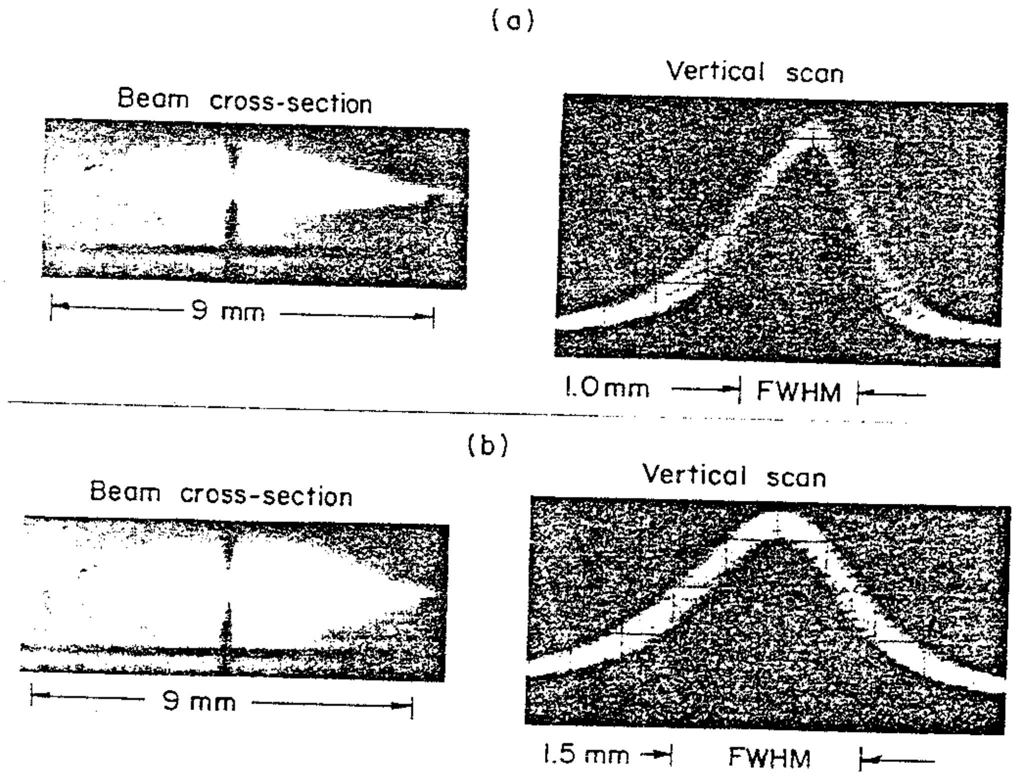


Fig. 10: Operating points in tune plane. Cross-hatched lines indicate regions of poor lifetime.



0750580

Fig. 9: Positron beam cross-section from synchrotron light, with vertical profile from scanner. Verticle profile is broadened in both cases by beam-beam effects. Beam current: 4.5 mA.

this vertical enlargement. Rotated (45°) quadrupoles have been used to artificially increase the coupling and broaden the beams vertically in an attempt to suppress beam-beam effects, and to equalize the horizontal and vertical tune shifts. There is some evidence the improved average luminosity results if the coupling is increased just enough to keep the beams free of self-sustaining coherent oscillations observed on the spectrum analyzer.

6.2 Injection Studies

Most of the effort in improving the filling rate has been directed toward making the coalescing process more efficient. There are at least 3 problem areas associated with this process.

i) The filling rate of multiple positron bunches decreases as the size of the individual bunches increases. This is especially true later in the fill cycle, when there is a large coalesced bunch circulating with the small bunches. It has been suggested that deflecting modes in the RF cavities[11] might cause this problem, but experiments that purposely shifted the beam through the cavities have not improved the situation.

ii) As the coalescing bunch is circulating in the synchrotron, the synchrotron magnets are changing strength slightly at the peak of their sinusoidal cycle. Since the re-injection efficiency into CESR depends sensitively on the energy of the bunch, some bunches are consistently more efficiently reinjected than others.

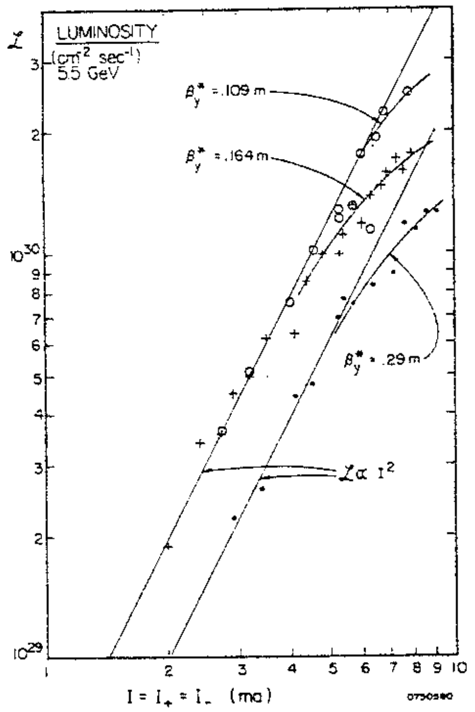


Fig. 11: Luminosity vs. current for 3 different values of β_y^*. Note L is proportional to i^2 for i<4 mA.

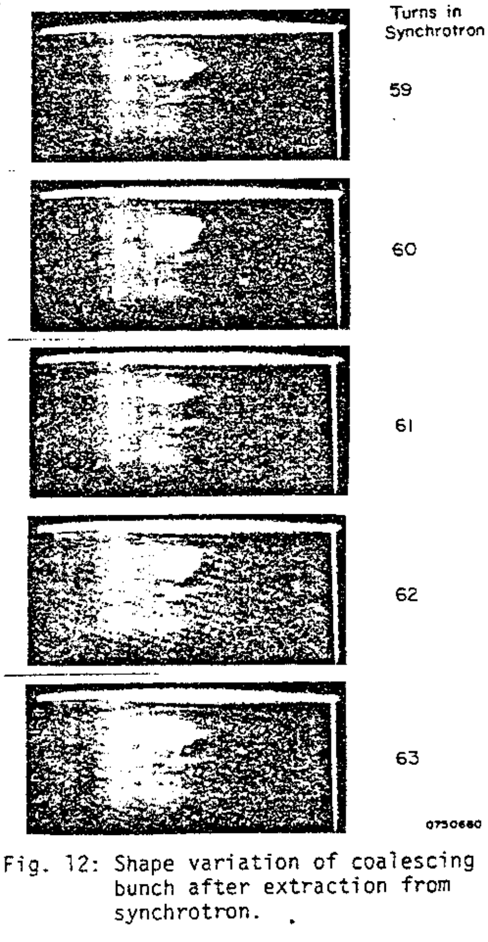


Fig. 12: Shape variation of coalescing bunch after extraction from synchrotron.

6. MACHINE STUDIES RESULTS

The goal of machine studies at CESR is to improve the performance of the accelerator as an instrument for high energy physics research. Two main approaches have been used: first, to improve the luminosity by learning how to reliably collide stronger beams while maintaining good lifetime, and second to reduce the filling time by learning how to more efficiently inject into CESR.

6.1 Luminosity Studies

Several areas of the tune plane have been explored to see if any was particularly advantageous from the point of view of lifetime and luminosity. Figure 10 identifies the operating points of the physics runs to date, and one area explored only during machine studies running. No one of the physics operating points has been judged clearly superior to the others, but it has been found that in each area of the tune plane relatively small changes in tune can lead to large changes in specific luminosity and/or lifetime.

The cross-hatched lines in Figure 10 identify regions of enlarged beam cross-sections or poor lifetime with two stored beams. In some regions of the tune plane the operating space is limited by the synchro-betatron sidebands of the $Q_H = Q_V$ coupling resonance. In other regions the operating space seems to be limited by third order resonances and vertical synchro-betatron resonances. Limitations due to resonances of order greater than 3 have not yet been seen. This complex situation is just now being explored systematically.

Luminosity vs. beam current current curves for lattices with 3 different values of β_y^*, the interaction region value of the vertical β-function, are shown in Figure 11. The peak luminosity for each lattice corresponds to a maximum vertical tune shift[10)]

$$\Delta Q_y = 2\ r_e\ \beta_y^* L/Nf\gamma \qquad (1)$$

approximately equal to 0.035. In the expression for ΔQ_y, r_e is the classical electron radius, L is luminosity, N is the number of particles per bunch, f is the rotation frequency of the bunches, and γ is the relativistic factor.

A similar calculation of the maximum horizontal tune shift ΔQ_x yields a value of approximately .027 for all 3 lattices. The calculation assumes $\sigma_x^* >> \sigma_y^*$ so we have[10)]

$$\Delta Q_x = Nr_e\beta_x^*/2\pi\gamma(\sigma_x^*)^2 \qquad (2)$$

where σ_x^* is derived from the theoretical horizontal emittance, energy spread, η^*, and β_x^*.

At beam currents i less than 4 mA, the luminosity L is proportional to i^2. In this region we expect σ_x^* and σ_y^* to be constant since

$$L = i^2/4\pi e^2 \sigma_x^* \sigma_y^* \qquad (3)$$

Using σ_x^* as calculated above, and σ_y^* calculated from the optically-measured single-beam emittance and β_y^*, the value of L calculated from the above expression agrees with the measured value to within $\pm 20\%$. The luminosity for the lattice with $\beta_y^* = 16$ cm. is higher than expected, for reasons not understood.

If all of the vertical emittance is attributed to coupling from the horizontal betatron motion via imperfections in the magnetic field, then the coupling constant (= vertical emittance/horizontal emittance) = 0.025 for a single beam or colliding beams weaker than 4 mA. At stronger currents with colliding beams, one or both the beams become enlarged vertically due to beam-beam effects. The positron beams shown in Figure 9 exhibit

iii) There is a great variation in shape of the coalescing bunch as it is extracted from the synchrotron, depending on the number of turns it has made in the synchrotron. The periodicity in number of turns is approximately 4, which corresponds to the vertical synchrotron tune of 10.75. Figure 12 shows a collection of various shapes seen on a flag just after the extraction point in the West transfer line. Some improvements have been made by attempts to better match the optical functions of CESR and the synchrotron, but there is still work to be done along these lines.

7. PROSPECTS FOR THE NEAR FUTURE

At the conclusion of the current physics run in July 1980, RF accelerating modules processed to 500 kW each will be installed in the East and West RF areas. The design energy of 8 GeV will then be attainable with beam currents of up to 30 mA. Peak luminosity of 10^{31} $cm^{-2}sec^{-1}$ should be within reach, if experiments with control of the vertical emittance to suppress beam-beam effects live up to their promise.

Improved diagnostics, including a vertical "pinger" magnet for exploring the vertical aperture, and a polarimeter for continuous monitoring of the polarization of the beams, will be installed. The feedback system, used to suppress coherent oscillations of the beams, will continue its development.

In the farther future, a superconducting RF accelerating module operating at 1500 MHz is being prepared for installation in the CESR ring. This experiment will provide the experience necessary for the continued development of this technology, which will be a crucial element in high energy e^+e^- storage rings of the future.

* * *

REFERENCES

1) M. Tigner, IEEE Trans. Nuc. Sci. NS-24, 1849 (1977).

2) D. Andrews, et al., Phys, Rev. Lett. 44, 1108 (1980).

3) T. Böhringer, et al., Phys. Rev. Lett. 44, 1111 (1980).

4) M. Billing, et al., IEEE Trans. Nuc. Sci. NS-24, 1370 (1977).

5) R. M. Sundelin, et al., IEEE Trans. Nuc. Sci. NS-24, 1686 (1977).

6) M. Tigner, Particle Accelerators 6, 4 (1975).

7) M. Sands, The Physics of Electron Storage Rings, Report SLAC-121, UC-28, University of California (1970).

8) R. Littauer, et al., IEEE Trans. Nuc. Sci. NS-26, 3275 (1979).

9) D. L. Hartill and D. H. Rice, IEEE Trans. Nuc. Sci. NS-26, 4078 (1979).

10) E. Keil, Perspectives on Colliding Beams, CERN/ISR-TH/74-22, IX International Conference on High Energy Accelerators, SLAC (1974).

11) R. M. Sundelin, IEEE Trans. Nuc. Sci. NS-26, 3604 (1979).